Alignment and calibration methods for the Belle II TOP counter

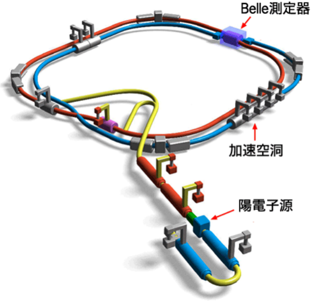
Marko Starič

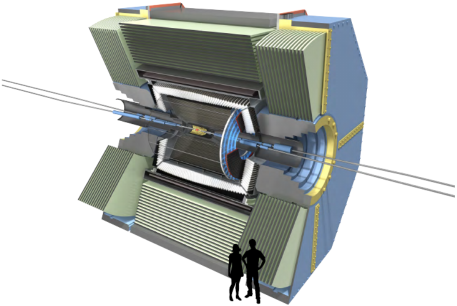
Belle II collaboration Jožef Stefan Institute, Ljubljana

RICH 2016 - Bled, Slovenia

Belle II experiment

- Successor of Belle experiment (KEK, Tsukuba, Japan)





SuperKEKB accelerator

- upgraded KEKB
- luminosity 40 × KEKB $(8 \times 10^{35}\mathrm{cm}^{-2}\mathrm{s}^{-1})$
- nano-beam optics

Belle II detector

- upgraded Belle detector
- majority of components replaced

Belle II environment

Critical issues at $\mathcal{L} = 8 \times 10^{35} \mathrm{cm}^{-2} \mathrm{s}^{-1}$

- Higher background (×10 - 20)
  - radiation damage and occupancy
  - fake hits and pile-up noise in EM calorimeter
- Higher event rate (×40)
  - affects trigger, DAQ and computing

Have to employ and develop new technologies to make such an apparatus work efficiently.

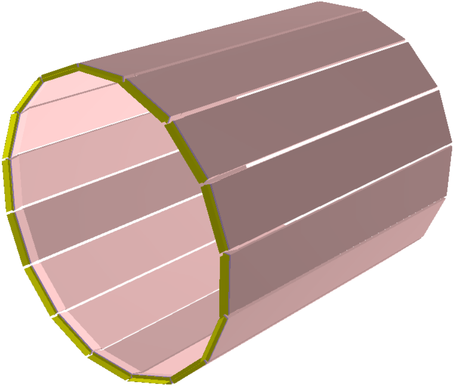
→ one of such technology is the Time-Of-Propagation (TOP) counter. (talks by J. Fast and K. Suzuki)

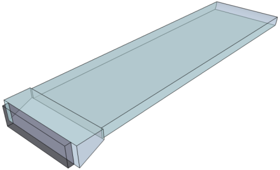
Belle II TOP counter

- 16 modules at $R = 120$ cm covering polar angles 32^0 - 120^0
- Quartz bars:
  - 2×45 cm^2 in cross section 2.6 m long
- Spherical mirrors:
  - radius of curvature: 6.5 m
- Expansion prisms:
  - 100 mm long, 51 mm high
- MCP-PMT:
  - Hamamatsu R10754
  - 2 rows of 16 per module

  → talk by K. Matsuoka
- Wave-sampling electronics

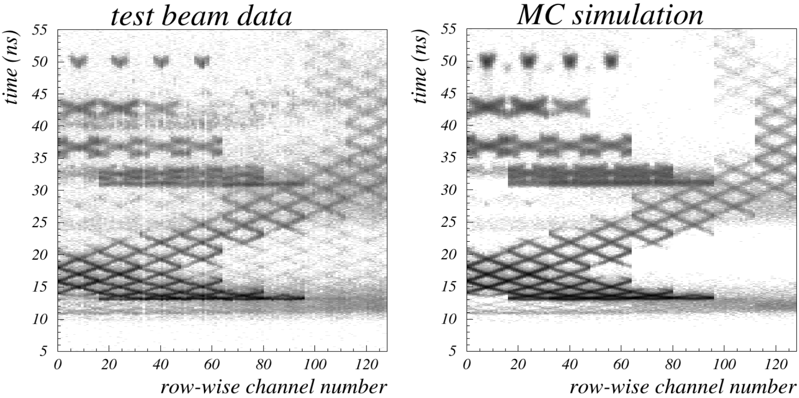
  → talk by G. Varner





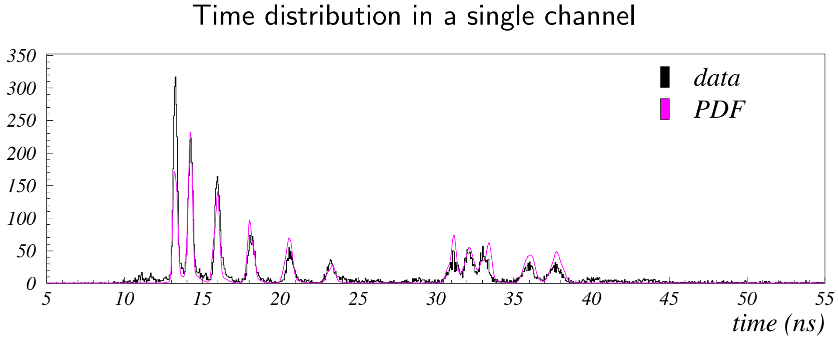
TOP counter response

- Ring image consists of complicated patterns
  - depends on particle impact position, angle and velocity



Perpendicular impact of a narrow 2.1 GeV/c positron beam
(data obtained at Spring-8 facility in Japan)

Particle identification: using extended likelihood method



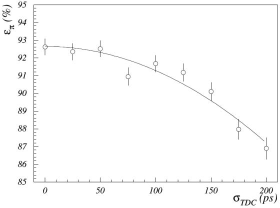
- PDF in a single channel described with a series of Gaussian distributions
  - positions, widths and normalizations determined analytically
  - method presented at RICH2010 (NIM A 639 (2011) 252-255)

Critical parameters

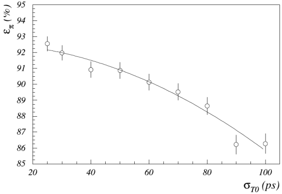
- single photon time resolution < 100 ps
  - TTS: 35 ps core Gaussian sigma (70%) + $\sim$1 ns long tail
  - electronic jitter $\sim$ 50 ps
  - channel offsets aligned to < 50 ps
- start time (T0) jitter < 50 ps
  - bunch length: 6 mm $\rightarrow$ 20 ps
  - TOF estimate uncertainly: 5 ps (from extrapolated track)
  - T0 calibrated to 5 - 10 ps precision
- module alignment better than extrapolated track precision
  - position: < 1 mm
  - rotation angles: < 1 mrad

MC study: $B^0 \rightarrow \pi^+\pi^-$

electronics jitter



T0 jitter



NIM A766 (2014) 237

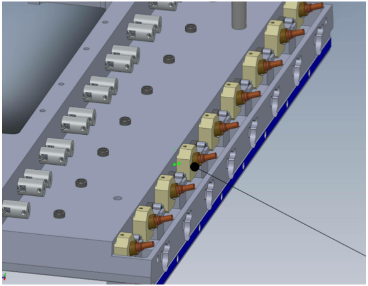
To be presented

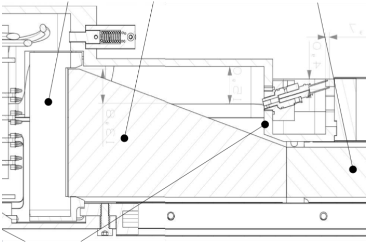
Methods for

- calibration of channel offsets
- module alignment
- real time T0 calibration

Calibration of channel offsets

- Dedicated pico-second laser calibration system incorporated into each module, consisting of 9 light sources (fibers) that illuminate MCP-PMT's from the slanted prism side.

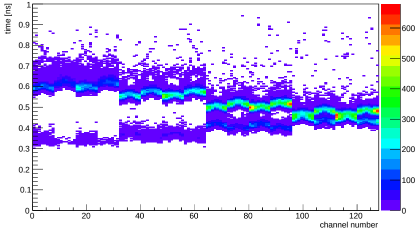


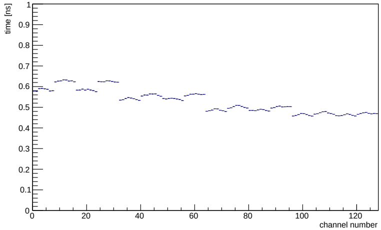


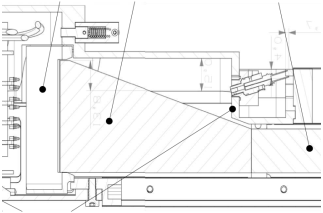
→ poster by U. Tamponi

Calibration of channel offsets

- MC simulation: photon propagation times


Photon propagation times vs. channel number


Average propagation time vs. channel number

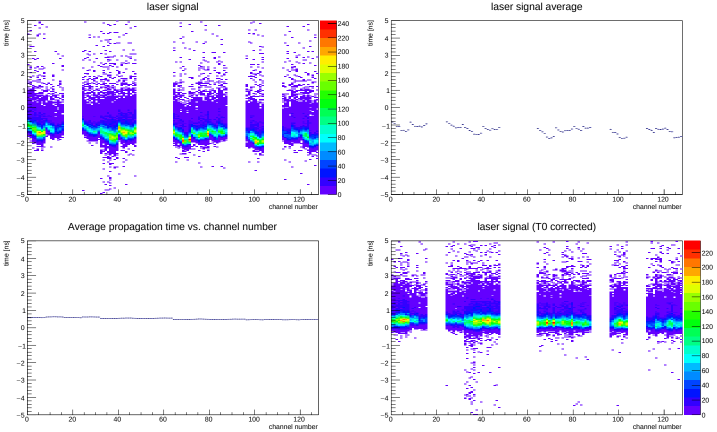


A robust method:

- align average of the measured distribution in each channel with the simulated propagation time average
- needs good knowledge of the fiber light angular distribution

Calibration of channel offsets

- Commissioning data example (preliminary)
    - offset = measured average - simulated one



→ work is ongoing, more refined methods on the way

Alignment

- Alignment of a module
  - find small displacements from its nominal position
    → shifts in x, y and z by $\Delta\vec{r} = (\Delta x, \Delta y, \Delta z)$
    → rotations around x, y and z by α, β and γ
- Positioning of a module:
  - first displace it:
    $$\vec{r}\,' = R_z(\gamma) R_y(\beta) R_x(\alpha) \vec{r} + \Delta\vec{r}$$
    (going from local to nominal frame)
  - then position the displaced module to its place in the barrel
    $$\vec{r}\,'' = R_z(\phi)(\vec{r}\,' + \vec{d}), \quad \vec{d} = (0, R, z)$$
    (going from nominal to Belle II frame)

Alignment: method

- Most suitable are di-muon events: $e^+e^- \to \mu^+\mu^-$
    - clean, low multiplicity events
    - two high momenta particles ($p > 3\ \mathrm{GeV}/c$)
    - known particle identity (muons)
- Free parameters: 3 shifts, 3 rotation angles, and start time offset t_0
- Minimize the sum of negative log likelihoods over many muons

$$\chi^2 \equiv -2\sum_{i=1}^{n} \log \mathcal{L}_\mu^{(i)}(\hat{p}) = \mathrm{min}, \quad \hat{p} \equiv (\Delta x, \Delta y, \Delta z, \alpha, \beta, \gamma, t_0)$$

where $\log \mathcal{L}_\mu(\hat{p})$ is calculated with our standard extended likelihood method using analytic PDF.

- Minimization can be done with MINUIT, however an iterative procedure similar to Kalman filter would be more suitable

Alignment: iterative procedure

Such iterative procedure can be derived in the following way:

- Suppose we have already minimized χ^2 using i muons:
  $\rightarrow$ vector of parameters $\hat{p}^{(i)}$ and corresponding error matrix $V^{(i)}$
- Taking the next muon we can write:

$$\chi^2 \equiv -2 \log \mathcal{L}_\mu^{(i+1)}(\hat{p}) + \Delta\hat{p}^T V_{(i)}^{-1} \Delta\hat{p} = \min$$

- Expand the first term into Taylor series up to the second order:

$$f(\hat{p}^{(i)} + \Delta\hat{p}) = f(\hat{p}^{(i)}) + \sum_j \frac{\partial f}{\partial \hat{p}_j} \Delta\hat{p}_j + \frac{1}{2} \sum_{j,k} \frac{\partial^2 f}{\partial \hat{p}_j \partial \hat{p}_k} \Delta\hat{p}_j \Delta\hat{p}_k$$

  where $f(\hat{p}) \equiv \log \mathcal{L}_\mu^{(i+1)}(\hat{p})$,
- and solve minimization problem analytically.

Alignment: iterative procedure

- Solution is the following iterative procedure:

$$U^{(i+1)} = U^{(i)} - D^{(i)}$$

$$V^{(i+1)} = [U^{(i+1)}]^{-1}$$

$$\Delta\hat{p} = V^{(i+1)}\hat{s}^{(i)}$$

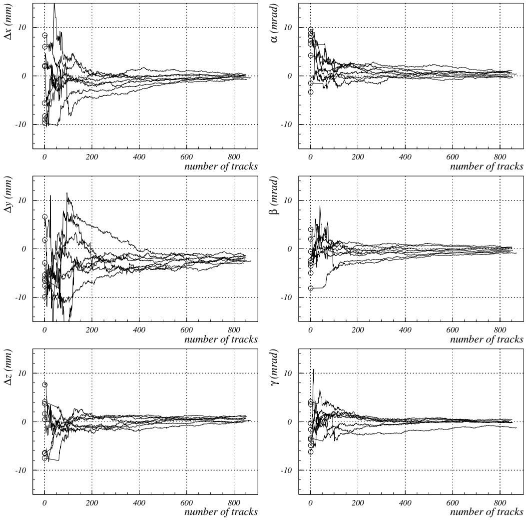
$$\hat{p}^{(i+1)} = \hat{p}^{(i)} + \Delta\hat{p}$$

Where:

  - $U = V^{-1}$, $U^{(0)} = 0$
  - D is matrix of second derivatives: $D_{jk} = \frac{\partial^2 \log \mathcal{L}_\mu}{\partial \hat{p}_j \partial \hat{p}_k}$
  - $\hat{s}$ is vector of first derivatives: $\hat{s}_j = \frac{\partial \log \mathcal{L}_\mu}{\partial \hat{p}_j}$

- First and second derivatives are calculated numerically.

Alignment: convergence



Convergence test with 8 different misalignments

Precision scales as

$$\sigma_x \approx \frac{14\ \mathrm{mm}}{\sqrt{n}}$$

$$\sigma_y \approx \frac{22\ \mathrm{mm}}{\sqrt{n}}$$

$$\sigma_z \approx \frac{12\ \mathrm{mm}}{\sqrt{n}}$$

$$\sigma_\alpha \sim \sigma_\beta \sim \sigma_\gamma \approx \frac{10\ \mathrm{mrad}}{\sqrt{n}}$$

$$\sigma_t \approx \frac{75\ \mathrm{ps}}{\sqrt{n}}$$

$\rightarrow$ need $\mathcal{O}(10k)$ muons to align a module

CPU: $\sim$ 0.6 sec./iteration

Real time T0 calibration

The reference time is given by the accelerator RF clock signal - within some arbitrary offset to the interaction time (start time) that has to be determined from data.

Method

- With di-muon events (known PID, clean events, high momenta)
- Maximize sum of muon log likelihoods for offset T_0:

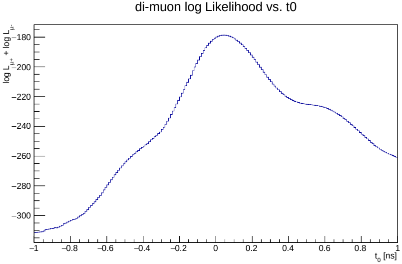
$$\sum_{i=1}^{N} [\log \mathcal{L}_{\mu^+}^{(i)}(T_0) + \log \mathcal{L}_{\mu^-}^{(i)}(T_0)] = \max$$

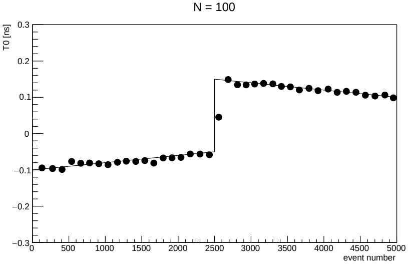
where N is the number of di-muon events and $\log \mathcal{L}_\mu$ are calculated with our standard analytic PDF based ext. likelihood method.

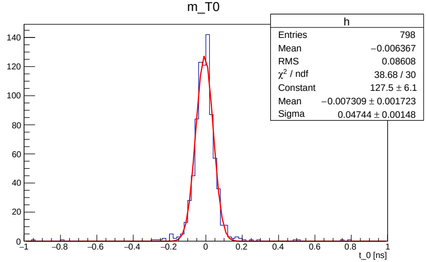
Real time T0 calibration

- Maximum is searched by performing a scan (local maxima sometimes present)
- Precision: ∼50 ps for N = 1
- Need $\mathcal{O}(100)$ di-muon events to get down to ∼5 ps
  → real time calibration possible

$N = 1$







Conclusions

- We've presented the methods for alignment and time-offset calibration of the Belle II TOP counter.
- Channel offsets will be calibrated with a dedicated laser calibration system that is part of the TOP counter.
- For the module alignment an iterative procedure was developed and tested with MC simulation. It is based on minimization of negative log likelihoods of muons from $e^+e^- \to \mu^+\mu^-$ events; the log likelihoods are calculated with our standard analytic PDF's.
- Real time T0 calibration is found to be possible; this method is also based on muon log likelihoods from our standard likelihood calculation.